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16. ABSTRACT

Over 120 facilities in the U.S. and Canada were surveyed to identify operational status and characteristics such as flowrates, equipment manufacturers, and upstream treatment processes. Six of these facilities were then selected for on-site inspections. The objective of the site visits was to determine the factors that contributed to the success or failure of UV disinfection. Each plant was inspected and its performance data were reviewed. Interviews were held with operators, supervisors, design engineers, and regulatory personnel associated with each facility. The evaluation concluded that UV disinfection equipment design has been the key to technology effectiveness and that manufacturers' designs continue to evolve rapidly. Electrical and mechanical difficulties often affected performance adversely. Poorly cleaned units have also adversely affected both the performance and economics of the process. Ease and safety of operating and maintaining the UV equipment caused operators to prefer this process to chlorination systems.

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FOCUS

A study of operational ultraviolet disinfection equipment at secondary treatment plants

Sam C. White, E. Barcus Jernigan, Albert D. Venosa

Ultraviolet (UV) disinfection of potable and industrial water has been practiced for several years; however, its use in disinfecting effluents from secondary wastewater treatment plants has been much more recent. Only since the 1979 publication of a national symposium on wastewater disinfection[1] has the application of UV disinfection increased at U. S. and Canadian secondary wastewater treatment plants. The principal forces behind the use of UV as a substitute for chlorination include efforts to protect sensitive species in receiving waters from the effects of chlorine compounds, and to reduce the possibility of injury to persons from accidental exposure to chlorine gas. Other reasons often cited to support UV disinfection include: lower life cycle costs, superior ability to kill viruses at typical dosages, the propensity of chlorine to form undesirable byproducts, and ease of operation and maintenance of UV equipment. UV disinfection of secondary effluent was boosted significantly when the U. S. Environmental Protection Agency (EPA) approved the technique as an innovative/alternative (I/A) treatment technology in several cases.[2] Venosa[3] summarized some of the more significant studies that contributed to the recent development of UV technology.

To determine the success of the UV systems financed through the I/A program, EPA undertook a project to evaluate the performance of representative operational UV disinfection systems. The project identified UV facilities throughout Canada and the U. S. and involved site visits to six selected systems. These site visits provided information on how UV technology was being applied in the field, and are the basis for many of the recommendations made in this paper. Two objectives of this study were to report the principal observations of the site visits and to make practical recommendations to design engineers. These practical considerations should allow more effective future applications of UV disinfection technology.

FUNDAMENTALS OF UV DISINFECTION

Mechanism of disinfection. Microbial cells contain nucleic acids, DNA and RNA, which store genetic information. To live and reproduce, the cell must be able to faithfully replicate the biochemical information in these nucleic acids. Nucleic acids will absorb light of different wavelengths, but demonstrate a maximum absorption when exposed to light between 255 and 260 nm. Low-pressure mercury vapor lamps generate light with a large majority of their spectrum at 254 nm, which is very close to the maximum absorption wavelength for DNA. Numerous studies have demonstrated that the 260-nm UV light has the strongest germicidal effect on microbes. UV irradiation is thus absorbed by the nucleic acids in microorganisms, and damages or modifies the genetic information. That damage renders a cell unable to replicate and results in death of that cell.

Disinfection model. From the Chick-Watson relationship and an analogy between the concentration of disinfectant and the intensity of UV irradiation, Luckiesh *et al.*[4] developed the following mathematical expression to describe batch-scale inactivation of bacteria with UV irradiation:

$$N = N_o e^{-kIt} \qquad (1)$$

Where:

N_o = Initial density of organisms (organisms/100 mL),
N = Density of organisms after irradiation,
I = Intensity of UV irradiation ($\mu W/cm^2$),
t = Time of exposure (seconds), and
k = Inactivation rate constant (sec^{-1}).

The equation indicates that increasing the product of the intensity of irradiation and time will reduce organism survival. That product is often referred to as the UV dose and is typically expressed in $\mu W\text{-sec}/cm^2$. Note that the relationship between the survival ratio (N/N_o) and UV dose is exponential.

Plant personnel seem to prefer UV systems to other types of disinfection, but because it is a relatively new technology, there are some risks involved in design and operation.

Practical application of fundamentals. In the design of a UV disinfection unit three basic areas should be considered: reactor hydraulics; factors that affect the transmission of UV light to the microorganisms; and properties of the wastewater to be disinfected.

Reactor hydraulics. To achieve the best performance from a UV unit, it is desirable to maximize mixing in the direction perpendicular to the flow (transverse dispersion) and to minimize mixing in the same direction as the flow (axial dispersion). The intensity of the UV beam dissipates as it passes through water; thus, organisms farther from the lamp are less affected. If mixing is maximized in the direction perpendicular to the flow (transverse dispersion or radial mixing), however, all the organisms move around and experience the same average distance from

the lamp. Adequate radial mixing can be achieved by designing the system for turbulent flow.

Axial dispersion is another issue altogether. In most disinfection processes, axial mixing has a major impact on the reaction kinetics of the process. When dispersion is low, the unit approaches plug flow and all the organisms are exposed to the disinfectant for the same length of time. When dispersion is high, short circuiting occurs and some organisms pass with little exposure. Trussell and Chao[5] illustrated this principle for chlorine contact tanks. Scheible,[6] Severin,[7] and Johnson *et al.*[8] all studied this problem in UV disinfection. Their studies confirmed that plug flow conditions are desirable and that short circuiting greatly reduces the performance of a UV unit. Low axial dispersion may be accomplished by minimizing turbulence at the entrance and exit of the reactor and by maximizing the aspect ratio (length/width) of the reactor vessel itself.

Transmission of UV light and quality of wastewater. Several factors must be considered in estimating the amount of UV light to which the organisms are actually exposed: the intensity of the UV radiation that eminates from the lamp itself decreases as lamp life increases; some lamp configurations provide a higher than average intensity in the flowing wastewater for the same level of energy input; some UV light is absorbed by the air, or by quartz or nonreactive fluorocarbon polymer surfaces, and the water which separates the lamps from the target organisms; and some UV light is captured by coating of quartz or nonreactive polymer surfaces with organic and inorganic materials on the water side and dust on the air side.

Consequently, plant maintenance should include replacement of UV lamps at regular intervals; reactor designs should be evaluated to determine their effectiveness in translating power consumed into average UV intensity in the water; consideration should be given to the absorption of UV by the wastewater; and surfaces should be cleaned regularly on both sides.

Wastewater characteristics will also affect UV system performance: initial bacterial density (N_o), absorbance of UV light, and suspended solids concentration. Ideally, the treated wastewater will readily transmit UV light, have a low N_o and a low suspended solids content that consists of very small particulates as opposed to larger aggregates of suspended matter. A review of performance specifications during the six site visits revealed that the UV units were intended for wastewaters with biochemical oxygen demand (BOD) and total suspended solids (TSS) concentrations less than 30 mg/L.

Most of the UV equipment specifications at the plants visited required that the wastewater absorb no more than 50% of UV light when passed through a 1-cm cell. Furthermore, large aggregate particulates tend to shield many bacteria from irradiation. These wastewater characteristics must be considered before UV is selected as a disinfectant and should be monitored frequently to evaluate system performance.

Microorganisms in wastewater must be exposed to a sufficient intensity of UV light for a sufficient period of time to obtain the desired degree of disinfection. The design engineer must know the factors that decrease intensity. Generated UV light must pass through a medium that separates the wastewater from the lamp. The two most common types of media are quartz or nonreactive fluorocarbon polymer because they transmit UV light. Many transparent materials such as ordinary glass are opaque to UV light. In systems where the lamps are submerged in the wastewater, sealed quartz sleeves are used to keep the lamps dry. In systems where the lamps are not submerged, nonreactive polymer tubes are used to contain the wastewater as it is irradiated from outside the tube. Both of these media absorb some UV energy and decrease the intensity transmitted into the wastewater.

A second factor that lowers intensity is any coating or film that may develop on the surface of these media. Dust can collect on the dry side of the tubes, inorganic scale can form on the wetted quartz or polymer surfaces, or a biofilm can grow on either surface. Obviously, these coatings can seriously decrease the effective intensity of the UV irradiation that reaches the wastewater and should alert the design engineer to the importance of keeping those surfaces cleaned.

Thus, the engineer should specify or select equipment that can deliver the required dose of UV light to the microorganisms. This requires an understanding of the wastewater characteristics, such as its UV absorbance and the initial density of microorganisms, so that the equipment can be properly sized. The equipment should provide good UV transmittance characteristics and intimate contact between wastewater and UV light, and should avoid hydraulic short circuiting that can hamper performance.

IDENTIFICATION OF UV FACILITIES

A study to identify UV installations in Canada and the U. S. was conducted in the spring of 1984 to determine the extent UV disinfection is used in municipal wastewater treatment. Telephone interviews with representatives of each state water pollution control agency and of each EPA region were conducted to identify the UV facility locations. In most cases, the representative was the I/A technology coordinator. Owners of each facility, or the associated design firm, were also interviewed to obtain more specific details.

Interview results. The study identified 35 municipal wastewater treatment facilities that were designed with UV disinfection, 31 that were under construction, 52 that were in operation, and eight that had been in use, but were now abandoned. Of these 126 systems, only 24 included some form of filtration before disinfection. Average design flow capacities ranged from what is expected to be the largest in the world—2.2 m^3/s (50 mgd) at Madison, Wis.—to 2.7 m^3/d (720 gpd). Figure 1 illustrates the distribution of design flow rates of the plants studied. As shown in Figure 2, the most common forms of secondary treatment used in the treatment plants are the oxidation ditch (31% of facilities) and the activated sludge process or its variations, extended aeration and contact stabilization (25% of facilities).

Field visits. One purpose of this study was to identify six operational UV facilities that could be visited for detailed inspections. The 52 operating facilities were using equipment supplied by six different equipment manufacturers. However, three of the six manufacturers accounted for more than 80% of the installations. Therefore, the six sites selected for detailed inspections consisted of three sets of two facilities chosen to represent each of the three most commonly installed brands. Sites that used filtration before UV disinfection were excluded from the selection because that configuration lacked technical risk, and was not considered to be an I/A technology. Other selection criteria considered were the design flow rate, current flow rate, and the secondary treatment processes upstream of the UV system. Final candidates were selected to represent a range of capacities, treatment types, and equipment suppliers. Table 1

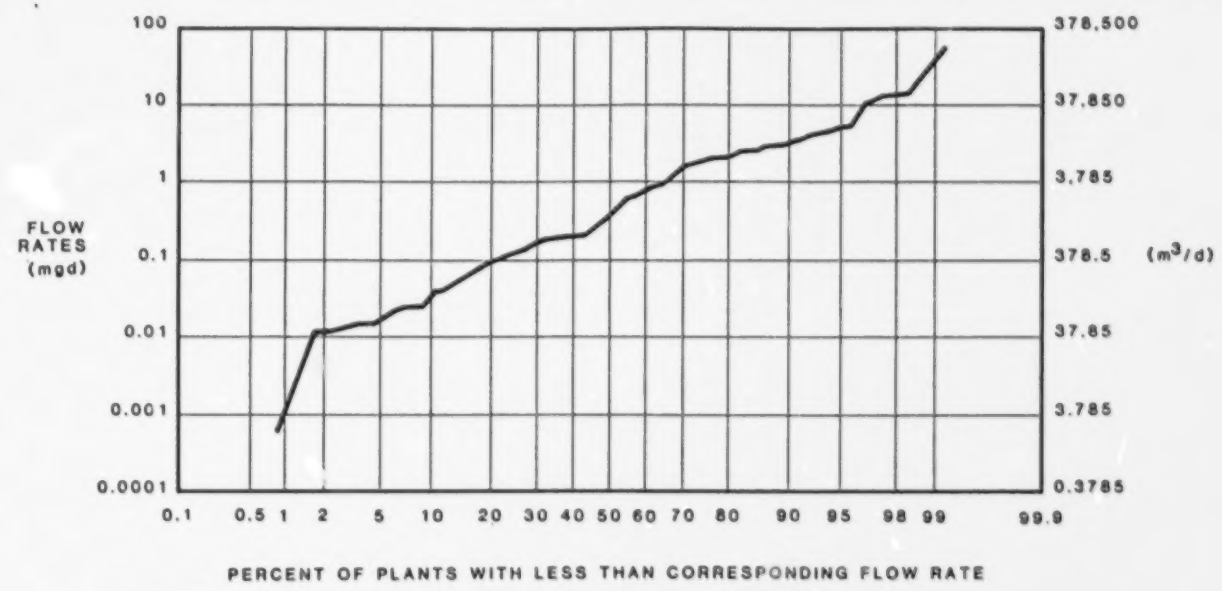


Figure 1—Distribution of design flow rates at wastewater treatment plants using UV disinfection.

compares the characteristics of the six selected sites. The sites are labeled A through F and the three equipment suppliers are designated as X, Y, and Z.

Table 2 summarizes some features of the six installations that were inspected. The lamps used at all six sites were rated at 65 W and required an additional 15 W for the ballasts. Therefore, each lamp required an applied power of 80 W. However, each lamp's actual output of UV light at 253.7 nm is 26.7 W and is subject to decrease by age or fouling. For comparison purposes, an exposure factor that reduces the various configurations and designs to a single value was calculated for each facility. These calculated values, included in Table 2, were found by dividing the total lamp output wattage by the design flow rate for that unit. The calculation was based on output rating of 26.7 W of UV light per lamp; the values are expressed as watts of UV light delivered per litre per second to the wastewater. The average exposure factor at the six sites was 38 W·s/L. However, the calculated factor does not account for variations in wastewater characteristics nor the effectiveness of the different equipment designs. For example, this factor does not account for actual contact time in the reactor; therefore, it cannot be correlated directly to performance. The design engineer who investigates a new UV system can compare its proposed exposure factor to these existing systems as one step in the process evaluation.

FIELD OBSERVATIONS

Each site visit involved interviews with supervisors and operators, a detailed inspection of the physical plant, a records review, interviews with the design engineering firm, and interviews with the state regulatory agency. Photographs, monitoring reports, and copies of plans and specifications were examined.

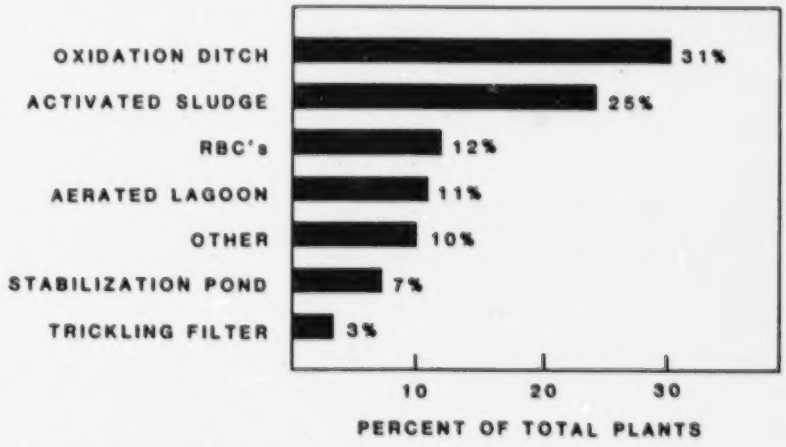


Figure 2—Types of secondary treatment plants.

Table 1—Characteristics of treatment plants visited in study.

Site	Average daily flow, m^3/s		Treatment processes[a]	Startup date	Limits for disinfection, fecal coliforms/100 mL	Effluent coliform monitoring requirement	Basis of UV design			Actual effluent TSS, mg/L	UV equipment manufacturer
	Design	Current					Peak flow, m^3/s (mgd) per unit	BOD/TSS, mg/L	Fecal coliforms/ 100 mL		
A	0.007	0.007	BS, C, PC, TF, EA, SC, D	April '82	None	2/wk	0.022 (0.5)	30/30	200	10–15	X
B	0.009	0.008	OD, SC, D	Nov '82	60	1/wk	0.013 (0.03)	30/30	60	16	X
C	0.10	0.04 to 0.12	C, AG, PC, AS, SC, BS, D	Nov '81	None	1/qtr	0.175 (4.0)	30/30	200 or 99.9%	15	Y
D	0.11	0.09	BS, AG, PC, TF, RBC, SC, BS, D	Aug '82	200 (30 day) 400 (7 day)	2/wk	0.100 (2.5)	30/30	100	16	Y
E	0.014	0.011	C, PC, RBC, SC, D	May '83	None	1/wk	0.028 (0.64)	"Treated Wastewater"	100	17	Z
F	0.083	0.053	BS, C, AG, PC, TF, IC, AS, SC, D	July '84	200 (30 day) 400 (7 day)	1/wk	0.175 (4.0)	"Treated Wastewater"	100	9	Z

[a] Sludge processing not included

Note—BS = Bar screen; C = Comminutor; AG = Aerated grit chamber; PC = Primary clarifier; RBC = Rotating biological contractor; AS = Activated sludge; OD = Oxidation ditch; TF = Trickling filter; EA = Extended aeration AS; IC = Intermediate clarifier; SC = Secondary clarifier; D = Disinfection.

Table 2—Features of UV systems at six inspection sites.

Site	Type	Configuration[a]	Design flowrate, m^3/s (mgd)	Exposure[b] factor (UV W · s/L)
A	Nonreactive polymer tube	Parallel-to-lamp flow, 30 lamps, single unit	0.022 (0.5)	36.6
B	Nonreactive polymer tube	Parallel-to-lamp flow, 24 lamps, two units	0.013 (0.3) per unit	48.7
C	Quartz sleeve	Perpendicular-to-lamp flow, 196 lamps (14 × 14 array), two units	0.175 (4.0) per unit	29.8
D	Quartz sleeve	Perpendicular-to-lamp flow, 144 lamps (12 × 12 array), two units	0.110 (2.5) per unit	35.1
E	Quartz sleeve	Parallel-to-lamp flow, 40 lamps, single unit	0.028 (0.64)	38.1
F	Quartz sleeve	Perpendicular-to-lamp flow, 260 lamps (7 or 8 × 35 rows, staggered), two units	0.175 (4.0) per unit	39.6

[a] Lamps used in all systems had an arc length of 147 cm (58 in.).
[b] $m^3/s = 10^3$ L/s, W · s/L = Joules/Litre.

Configurations. Some significant features of the various configurations at the six sites are illustrated in Figure 3. The two major categories of units used either UV lamps protected by quartz sleeves and submerged in the wastewater flow, or wastewater flow carried through tubes and surrounded by UV lamps. For the quartz sleeve units, the flow was either perpendicular or parallel to the lamps. For the lamps arranged perpendicular to the flow, the adjoining rows were generally staggered and the lamps were spaced vertically or horizontally, depending on the manufacturer. Some units were designed to operate under pressure; others used gravity flow hydraulics. Overflow weirs were used typically to control flow distribution and maintain optimum water levels in the gravity units.

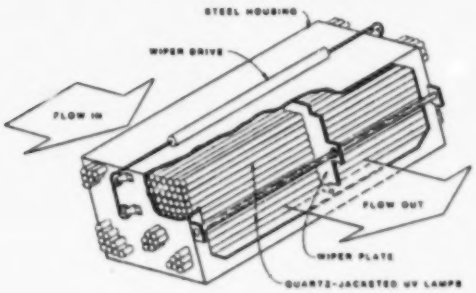
The location and configuration of associated electrical components also varied from site to site. All tube units had wiring, ballasts, and indicators mounted within the body of the UV reactor unit itself. This was possible because the lamps were dry and did not need to be separated physically from these electrical components. All four systems with quartz sleeves submerged in wastewater used remote electrical control panels to house ballasts, relays, meters, and other instrumentation.

There seemed to be no consensus among manufacturers as to the best configuration. Indeed, the geometry of the units produced by a single manufacturer has changed radically over short periods of time. All six installations inspected in this program had begun operation within a span of less than 3 years. In addition, less than 1 year separated the start-up dates of facilities supplied by any single manufacturer. Yet, even within this narrow time frame, the inspections revealed that equipment designs had changed substantially.

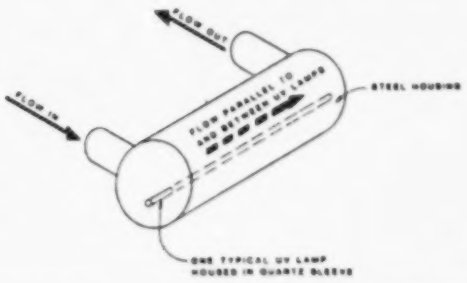
Some equipment features at these six installations were not consistent with the practical application of fundamentals previously discussed. For instance, units constructed as in Figure 3 (Part A) do not promote plug flow through the battery of lamps. Those systems are very wide, relative to the shorter longitudinal flow direction (length). This configuration is susceptible to short circuiting and uneven irradiation of the unit throughput. However, this configuration does promote intimate contact of wastewater with the UV radiation. Its perpendicular-to-lamp flow pattern and relatively close spacing (1.27-cm between quartz surfaces) generates turbulence that improves the probability of intimate contact between all microorganisms and the UV radiation.

A unit of the type shown in Figure 3 (Part B) also had some design features that seemed inconsistent with the fundamentals. An end view of that unit is depicted in Figure 4. The parallel-to-lamp flow pattern would have approached plug flow more closely if the inlet and exit piping were not perpendicular to the flowpath. There is no internal structure to re-direct the flow by 90°, or to distribute the flow evenly across the end of the unit. More importantly, the system did not provide the intimate contact between wastewater and UV light when all lamps were not illuminated. Figure 4 shows the pattern of lamps when two of the four banks of lamps were used. Because the illuminated lamps are unevenly distributed throughout the chamber, a significant fraction of wastewater may pass through the system with insufficient irradiation. This system should operate with all four banks illuminated constantly to keep wastewater from bypassing irradiation.

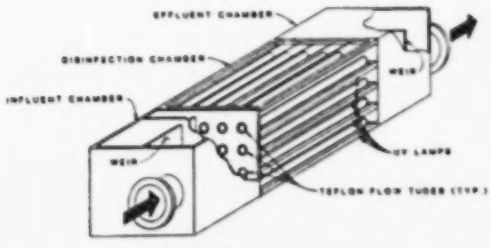
An early model of a nonreactive polymer tube unit, illustrated in Figure 3 (Part C), distributed the wastewater flow unevenly throughout the tubes; therefore, some of the wastewater did not receive adequate irradiation. This problem with hydraulics seems to have been remedied by a reconstruction of the influent chamber to use all flow-tubes at all times. The original problem resulted from an attempt to match UV output to flow rate by allowing some lamps to be turned off at low flows. A weir system in the influent chamber was intended to restrict flow to selected tubes



A) PERPENDICULAR-TO-LAMP FLOW IN A QUARTZ UNIT



B) PARALLEL-TO-LAMP FLOW IN A QUARTZ UNIT



C) TEFLON-TUBE UNIT

Figure 3—Typical UV disinfection equipment configurations.

at low flow conditions; however, this caused uneven flow rates through the unit. In subsequent installations, all flow-tubes are used at all times and the UV lamps stay illuminated continuously. Later models of the tube units used long tube lengths to make the flow characteristics more like plug flow.

Ventilation. Electrical problems at three of the six sites were apparently caused by inadequate ventilation of the heat-generating electrical components. Ballasts, relays, and meters housed in metal panels require ventilation to avoid excessive temperatures that could lead to early failure. Equipment at three of the sites had experienced these elevated temperatures with subsequent failures and had been modified to correct the problem. Larger ventilating fans and more louvered vents were provided to alleviate the build-up of heat in these panels. The design engineer should use the expertise of an electrical engineer and require adequate ventilation in the specified equipment. Furthermore, proper ventilation should be provided for the entire structure that houses the UV system.

Cleaning. The medium that separates the lamps from the wastewater must be kept clean to maximize the dose of UV radiation that reaches the microorganisms. Three common cleaning methods are ultrasonics, mechanical wipers, and chemical cleaning.

Ultrasonic transducers were installed in two of the quartz sleeve units, but both units also required supplementary chemical cleaning. While ultrasonic generators are set to operate intermittently, the operators have no means to determine how effectively the units are cleaning. The only true test of cleaning effectiveness would be influent and effluent measurements for fecal coliforms, both before and after cleaning. These analyses would allow comparisons of kill ratios before and after cleaning, but such evaluations were not performed at either installation. The UV intensity meters installed on these units were not sensitive enough to detect differences in intensity before and after the ultrasonic transducer was used. Kreft *et al.*[9] addressed this issue with field tests of the cleaning equipment at various sites.

Two submerged quartz sleeve facilities, Sites C and D, use mechanical wipers to clean accumulations from the wetted surface of the quartz. As illustrated in Figure 3 (Part A), these mechanisms use rubber or nonreactive polymer rings around each sleeve, and they wipe the quartz intermittently. However, both facilities also use chemical cleaning occasionally; the wipers are intended to extend the time between chemical cleanings. As with ultrasonics, the mechanical wiper system does not allow the operator to evaluate the effectiveness of the cleaning mechanism. Therefore, both sites have established a set interval for chemical cleanings. It would be necessary to shut down and drain the systems to inspect the quartz surfaces. Even then, only the surfaces of sleeves near the edges of the lamp array could be inspected easily.

Chemical cleaning has been recommended by the suppliers as the primary cleaning method for the two tube facilities. All four quartz facilities have also adopted this method to supplement either ultrasonics or mechanical wipers. The cleaning agents recommended by equipment manufacturers vary from soap and water to acid solutions. A simple soap and water washing under high-pressure flow was recommended for one of the tube units. Solutions of citric acid, sulfuric acid, sodium hypochlorite, sodium hydrosulfite, and commercial acid detergents have all been used to clean quartz sleeves. To complete the process, most quartz units had to be taken off-line, undergo recirculation of the cleansing solution, be drained of the cleansing

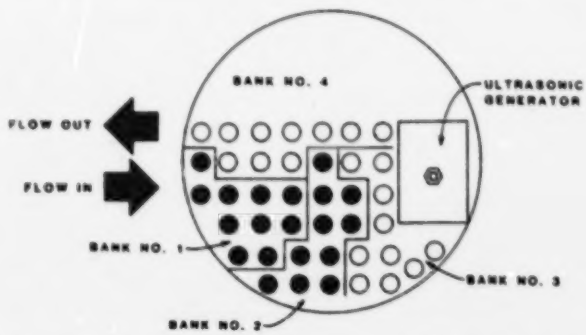


Figure 4—End view depicts lamp arrangement of unit in Figure 3(B).

solution, and be put back on-line. Disposal of the cleanser must be considered by the design engineer. In various cases it was pumped back to the head end of the plant, held for gradual discharge, or held and reused.

It is also necessary that the dry side of the tubes be kept clean of dust or other accumulations. The tubes can be wiped occasionally with a damp cloth, and the entire lamp rack enclosure should be ventilated with filtered air to prevent such a buildup on dry surfaces.

Operation and Maintenance. Two attractive features of UV disinfection are simplified operation and lower maintenance requirements compared to other disinfection technologies such as chlorination or ozonation. However, these systems are not attention-free and, to be effective, the process must receive the proper amount of operator attention and maintenance.

Process control. Very little operator effort is required during routine disinfection operations that use UV equipment. Once the equipment is turned on, the only variable available to the operator is the amount of irradiation supplied to the wastewater, or which unit(s) is (are) to be used. In most installations the operator can determine the number of lamps to be illuminated or the power to be applied. Once the UV dose is set, the operator need only monitor the system to confirm that the status is maintained until a change is desired. All six systems are equipped with sensors for each individual lamp. These sensors provide remote indications so the operator can determine which lamps are illuminated.

One factor that influences the applied power level is the flow rate. At low flows and higher detention times in UV units, it may be desirable to reduce the total amount of irradiation to conserve power costs. Five of the six sites were designed with controls that were intended to automatically adjust lamp output to be proportional to the flow rate. Use of the automatic control has been discontinued in four of those five plants. The newest plant, Site F, had begun operation just before the inspection visit. The only facility that was not designed with an automatic control feature was Site B; in that tube system, all 24 lamps of a unit were either on or off at all times.

The automatic systems had been replaced by manual control for various reasons. At the other tube facility, Site A, the original design attempted, unsuccessfully, to use overflow weirs and flow-splitting devices to trigger the illumination of lamp banks during elevated flows. The unit was modified subsequently to operate in the same manner as Site B, with even flow distribution to all tubes and all lamps continuously illuminated. Sites D and E were found to be performance-limited and could not reduce dosage; they needed more capacity, not the ability to reduce output. However, Site D had experienced electrical difficulties earlier, when the use of automatic controls was attempted, and then discontinued when it was discovered that the facility was performance limited. The electrical problems with the lamp controllers were never resolved satisfactorily. Faulty wiring and burned-out circuit boards were replaced, but the controllers were not used for any long period to demonstrate their effectiveness. Five electrical fires occurred at the control panels when operated in the automatic mode. No fires were reported after manual control of lamp bank illumination was resumed. Site C was designed to have power to the lamps controlled by a microprocessor that had flow rate and other variables built into its logic. It was a complex control system, for which the owner had difficulty getting service after the individual who invented and programmed the apparatus retired. Therefore, the plant reverted to manual controls.

The ability to conserve power consumption when performance goals are being met is important and should not be ignored by a design engineer. However, based on the experiences at these sites, any automatic control used on UV systems should be reliable, be easily maintained by the plant staff, and use proven, readily available parts and instruments. A simple mechanical cam timer, which shuts off selected lamps, or banks of lamps, to reduce UV output during a selected time period every day to match diurnal flow patterns, could be as effective as a more costly microprocessor-controlled system.

Other elements of process control that require operator attention and care are laboratory analyses and record keeping. The only way to ensure that the selected power levels are correct and that the process is under control is to analytically measure the performance of the unit on a frequent basis. Reliance on in-place UV intensity meters has not been successful at the study sites. The sensors cannot indicate adequately the intensity actually being delivered to the entire flow of wastewater, and are not sensitive enough to be useful in actually controlling the units. Internal UV sensors are subject to the same fouling phenomena that the quartz and tube units experience. To be useful, a large amount of analytical data would have to be correlated to readings from such a meter. Based on results from this study, these meters were not, and should not, be relied on for control. However, they were useful as a device to signal loss of all UV illumination from a bank of lights. A sampling program can provide the necessary data to assess the treatment. This sampling program will require more data than is normally monitored for the monthly permit reporting. The operator should collect and monitor the data so that appropriate control actions can be taken.

Maintenance. The maintenance of a UV system is the most important aspect of operation of these units and should consist primarily of four separate tasks:

- routine chemical cleaning of the system,
- periodic replacement of lamps, ballasts, and quartz or non-reactive polymer surfaces,
- periodic replacement or repair of electrical components such as meters, relays, and indicator lights, and
- an annual cleaning, overhaul, and repair of the system.

The frequency of cleaning at the six sites varied greatly because of the three different equipment designs and the different wastewater characteristics. Chemical cleaning may be used on a predetermined schedule or in response to indications of declining performance. Individual lamps and ballasts must be replaced periodically as these components age. Each UV unit at these sites was equipped with elapsed-time meters. While a complete log book should be kept to record the date and elapsed time on a unit when a maintenance function, such as lamp or ballast replacement, is performed, only half of the six installations had such a log of their UV maintenance activities.

One of the complaints voiced by operators about the UV systems was that a trained electrician was needed for anything beyond replacement of lamps or ballasts. The majority of these complaints were generated by the frequent electrical problems experienced during startup and initial operation. Such difficulties and problems following startup were cited by personnel at all

six sites. Consequently, a treatment plant supervisor should take steps to assure that a trained individual is either on staff or readily available through a contractual arrangement to respond to such needs.

PERFORMANCE

The performance of a UV system can be expressed in terms of its kill ratio or the fecal coliform count of its effluent. A system could produce a three log reduction (99.9% kill) of fecal coliforms, but still violate a permit limit expressed as an absolute number. To adequately assess performance, the following data should be available for a UV unit:

- fecal coliform entering the unit (N_o),
- fecal coliform exiting the unit (N),
- TSS entering the unit,
- absorbance (or percent transmittance) of wastewater,
- flow rate at the time of sampling, and
- number of lamps illuminated at the time of sampling.

These data should be based on grab samples, not composites or daily averages. If these data were monitored frequently, the operator or supervisor would have the facts available to evaluate the effectiveness of the unit, the need for cleaning, and the effectiveness of cleaning. Unfortunately, these data were not normally available at the sites visited in this study because most sites, at present, collect only the data required for periodic regulatory reports.

Examinations of facility records during the site inspections did not produce all the data necessary to adequately evaluate performance of those UV systems. None of the sites routinely measures influent fecal coliforms; therefore, no information on kill ratios is available. All six sites monitored effluent TSS and effluent fecal coliform counts, but the TSS was based on composite samples while the fecal coliform counts were obtained on grab samples. However, it should be noted that all six sites were discharging effluents that were of better quality, with respect to TSS and BOD, than was required by permit. The UV units at these plants were receiving well-treated secondary wastewaters with TSS concentrations well below their design limits and flow rates at, or below, design levels. Neither the instantaneous flow rates through the units, nor the number of lamps in use were available to be matched with effluent fecal coliform data. The primary data element that is measured for most UV systems is the effluent fecal coliform count because it is usually a required entry on a monthly monitoring report form.

Portions of the performance data reviewed during the six site inspections are summarized in Table 3. Note that the fecal coliform discharge levels reported may represent operations of longer than a year, or may be based on as little as 2 months of operating data. An attempt was made to present data from each unit representative of its performance at the inspection time. At half of the sites (A, C, and E), data were available over a sufficient time period to provide a reliable indication of performance. Other sites provided only short data histories, as noted, because major equipment modifications or prior plant operations made earlier UV disinfection data unrepresentative.

The data in Table 3 indicate that the two sites (A and E) that have no fecal coliform limit specified in their NPDES permit are producing effluents with fecal coliform counts much higher than would normally be allowed in most permits. Of the six facilities, only Site C with its extended and consistent data history can be said to be performing within regulatory requirements. Site B is recovering from an earlier upset in the biological system and may soon meet its permit requirements more consistently. Site D can meet its requirements only if current flow is divided between both of its units while using all banks of lamps. Each of those units was intended to have approximately double that capacity. Finally, the new plant at Site F seems capable of meeting its permit requirements, but no real data history is available currently, and the new treatment plant had just begun operation at the time of this investigation.

As emphasized earlier, design of the equipment can drastically affect performance. For effective disinfection, a UV unit must bring wastewater into intimate contact with UV irradiation long enough to obtain the desired reduction of organisms. Data chosen from Site D illustrate this principle. The UV equipment at Site D was not performing as expected. A close examination and measurements revealed that the unit had not been built according to shop drawings. The unit is the type depicted in Figure 3 (Part A). The fabrication error allowed the stream of wastewater which passed over the topmost row and under the bottom row of UV

Table 3—Effluent fecal coliform levels.

Site	Permit limits fecal coliforms/100 mL 30-day average	Discharge fecal coliforms/100 mL 30-day average	Comments
A	None specified	490	Monthly means ranged from 110 to 1800 between 4/83 and 4/84.
B	60	65	Based on data from 4 months (April–July 1984) following a major upset to the treatment plant.
C	200	74	For the 7 reporting months of 1983.
D	200	150	Based on data from 2 months (Nov and Dec 1983) following correction of a fabrication error.
E	None specified	930	Based on data from 6 (Sept 84 to Mar 85) when all 40 lamps were used and system was chemically cleaned every 1–2 weeks.
F	200	—	New plant startup, no data history.

lamps to be more than 1 in. thick instead of the 0.25 in. specified. Therefore, approximately one-fifth of the total unit throughput was not exposed adequately to UV irradiation. After the error was discovered, the units were modified and performance improved. Data taken from monthly operation reports over a 6-month period are presented in Figure 5 to illustrate the poor results caused by the hydraulic short circuit and the improved performance that followed the modifications. Subsequent testing at the site has indicated that its performance has possibly been further hampered by an uneven distribution of flow across the face of the unit. Because the flow path through this unit has a relatively short length-to-width ratio, its performance is sensitive to such uneven distributions.

The design engineer who is aware of the fundamentals of UV disinfection can evaluate disinfection equipment designs much more thoroughly. Furthermore, the design engineer can enhance system performance by applying good engineering design concepts that consider hydraulic flow distribution, system control, and maintainability, and by establishing analytical requirements to assure proper data are collected to assess and control performance.

COSTS

A curve was prepared for EPA in 1984 by Scheible *et al.*[10] to estimate equipment costs for various sizes of UV facilities. The curve reflects the combined costs of the UV reactor, its power supply panels (ballasts), control instrumentation, cleaning equipment, replacement parts, and installation. This cost curve is presented as the solid line in Figure 6. It was constructed from actual bid prices provided by various UV equipment manufacturers in 1984. For comparative purposes, the capital costs of UV facilities at the six inspection sites are depicted as points on Figure 6. These costs are for the equipment only and do not include allowances for structures to house them. The system size for each of the six sites was obtained by multiplying the number of UV lamps by 80 because all six sites used lamps rated at 65 W with ballasts that required an additional 15 W.

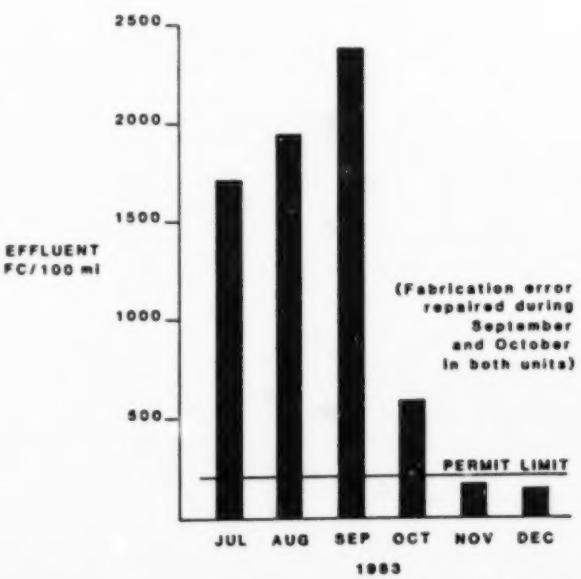


Figure 5—Improved effluent quality at Site D after correcting a fabrication error that was allowing a partial bypass through the UV unit.

Capital costs for five of the six sites visited have exceeded the value predicted by the 1984-based estimating curve. Manufacturers bid on the six sites earlier in the development of UV application to wastewater and probably reflect some development costs. The lower costs of the 1984-based curve could be the results of increased competition and design improvements.

Costs for housing the UV systems were not readily available, but are estimated to vary greatly. The UV system at five of the six sites is housed inside a structure for protection from the elements; only Site C is outdoors. Floor space dedicated to the UV systems was not always proportional to the system size (kW), because some models were more compact and had less of a requirement for control panels or cleaning equipment than others. The design engineer should allow for floor space to accommodate the reactor, cleaning accessories, power supply cabinets, and maintenance access in the cost estimate.

Operations and maintenance costs for UV disinfection can be categorized as follows: manhours for routine maintenance; replacement parts and supplies; power utilization; manhours for analytical work; and cleaning chemicals.

Operations and maintenance costs for the six inspection sites were also not readily available for various reasons. The owners at three sites had not yet accepted equipment from the contractor, and thus had not incurred or recorded any costs for replacement parts or maintenance at the time of the inspections. Some sites had not been in operation long enough to establish an estimate of routine maintenance. Furthermore, the large majority of plants were not able to document the portion of total power use that was dedicated to the UV system. Most of these facilities are not provided with a meter that records power use by the UV system alone. Therefore, the only means available to estimate power costs is to attempt to recall (from records or from memory) which banks or lamps had been used during any period. For systems where power use was automatically related to flow rates, no accurate means of estimation is available without separate metering for the UV system.

Based on interviews and observations from the six site investigations, manhour resources, which should be allocated to maintenance and operation of UV systems, are estimated as follows. Smaller facilities (less than 100 lamps) should allocate approximately 8 manhours per week to accomplish the routine maintenance tasks, which include the three sets of analyses described earlier. Larger systems (greater than 200 lamps) should allocate approximately 12 manhours per week for maintenance, which includes up to five sets of analyses for process evaluation. These manhours may be divided between laboratory personnel and a maintenance staff if the staff is large. All these tasks will probably be accomplished by only one or two individuals at smaller facilities.

RECOMMENDATIONS

Interviews and UV facility inspections revealed that the engineers who design wastewater treatment plants do not have access to definitive references when designing the UV disinfection process. Application of UV to disinfection of secondary effluents

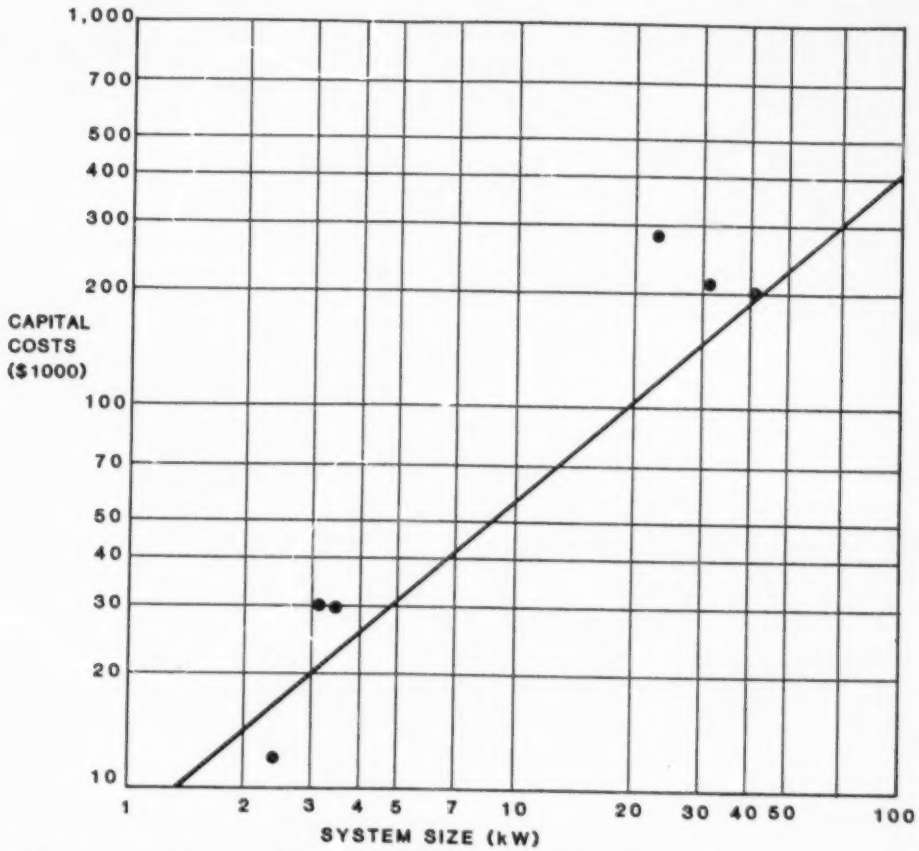


Figure 6—Capital costs for UV equipment at six sites compared to previous EPA-supplied estimating curve.

is a relatively new development; therefore, engineers do not have much historical background on which to base designs. As a consequence, most engineers have used performance specifications and left the details of the process design to equipment manufacturers.

The technology has now been in use for a few years and it is possible to draw on that experience to make more informed decisions and allow design engineers to take more active roles in designing and sizing UV disinfection processes. A comprehensive guide is needed to provide engineers with rational design criteria and procedures to follow when the UV process is chosen for disinfection. However, until such a comprehensive publication is available, the following recommendations can be useful. This list contains issues for the designer to consider, suggestions, and specification-related details on UV disinfection systems.

- Wastewater characteristics should be consistent with UV disinfection. The wastewater should contain low TSS concentrations, preferably 20 mg/L or below, and transmit at least 50% of UV light through 1-cm wastewater. This absorbance of UV light is typically measured in a spectrophotometer set at 253.7 nm using a quartz cell, or cuvette, which provides a 1-cm pathlength through the wastewater sample. The wastewater should also be analyzed for components that may lead to inorganic fouling of nonreactive polymer or quartz, for example, calcium, magnesium, and iron.
- Pilot testing is recommended to establish design criteria. There seems to be no consensus on the dose required for disinfection. Given the lack of such criteria, on-site testing seems to be the best way to attain a reliable design basis. On-site testing will also provide an opportunity to estimate the required cleaning frequency and an appropriate cleaning agent.
- The engineer should provide adequate space around the UV units to accommodate maintenance activities. Many units use lamps that are 1.5 to 1.8 m long; therefore, sufficient space at the sides or end must be provided to allow those lamps to be replaced. Some units need a certain vertical clearance above them because the lamp racks must be raised above the unit for lamp removal. Those units must be mounted at floor level or other provisions should be made for personnel to stand on a stable structure when changing lamps.
- The equipment design should allow one person to readily remove and replace lamps without the use of special tools.
- The ballasts should be arranged such that the operator has ready access and can remove or replace any ballast without having to remove others. The ballasts should not be gang-mounted such that access to one is hindered by one or more others. In addition to the inconvenience, gang-mounting many ballasts

into a small space has led to overheating and ventilation problems and should definitely be avoided.

- The engineer should require the manufacturer to comply with certain minimum electrical standards of construction consistent with the location or environment that surrounds the UV unit and associated equipment.
- The engineer must provide floorspace for any separate components of the UV system in addition to the UV reactor itself. Requirements for power supply cabinets or cleaning equipment must be factored into the layout.
- The engineer should provide adequate ventilation to the structure housing the electrical components of the system. Given the maximum temperature allowed in that structure, the engineer should require that the manufacturer provide assurance of adquate ventilation of the power supply cabinets to prevent failures from overheating. That assurance should reference the critical temperature at which the first component (ballasts, for example) would fail. Failure to provide adequate ventilation has been a frequent cause of electrical problems at the sites visited.
- The engineer should assess the various means of chemical cleaning available. Does the method require the unit to be drained? What volume of cleansing agent is required per cleaning? What is the disposition of that spent cleaning solution? What are the manpower requirements to accomplish a cleaning cycle? What are the capital costs of the cleaning equipment? How expensive is the cleaner? Is it readily available? Does it require special storage and handling considerations?
- The engineer should require the manufacturer to equip the units with combinations of UV lamps and ballasts that are matched and intended for combined use. Lamp manufacturers recommend specific ballasts for use with different lamps. Because the UV lamps use a higher voltage than normal fluorescent lamps, the ballasts typically used for fluorescent bulbs are not appropriate. The ballast is matched to the lamp's length and operating characteristics to provide a current wave shape optimized for that lamp. The proper matching of lamp and ballast will improve the lamp's output and extend its useful life.
- The equipment design should allow the system to be drained easily. Does the unit have a bottom cleanout port to allow removal of deposits or accumulations?
- The engineer should specify the use of modular construction with multiple units to allow uninterrupted service when performing maintenance.
- The UV system should be metered separately to document power consumption of this process alone.
- The engineer should assess competitive designs for compliance with sound application of the fundamentals of UV disinfection theory. Do the units promote plug-flow hydraulics? Is the wastewater retained in intimate contact with the UV light for a sufficient period? Are the designs susceptible to short-circuiting? If all lamps are not illuminated, will some wastewater escape irradiation (parallel-to-lamp flow)? The engineer may request that tracer test results be provided to document hydraulic characteristics.
- If ultrasonic cleaning is used, does the design allow or call for wastewater to flow over non-illuminated banks? This situation can lead to biofilm grown on non-illuminated quartz sleeves.
- The design engineer should allow adequate staffing and resources for the data collection and monitoring required to assess performance. This should include frequent sampling (three to five sets per week) at the unit as described earlier in the discussion on performance. The engineer should establish the monitoring and analytical logs to support that program, and should provide adequate manpower to perform routine maintenance.
- Construction materials should be consistent with wastewater and the environment. Engineers commonly specify 304 stainless steel for the UV chamber of the quartz sleeve units. Some rubber and plastics, when exposed to UV irradiation, are subject to degradation.
- The operator should be able to determine if each individual lamp is illuminated.
- The system should have provisions for decreased power consumption during low flow situations. How is the power controlled? Is the control process overly sensitive to flow variations? Can the system be maintained by the plant staff? Modular construction with multiple units would be preferred to shutting off banks of lamps within a single unit.

SUMMARY

Disinfection of secondary wastewaters can be accomplished with UV light; however, because it is a new application of technology, some risks are associated with its practical use in secondary wastewaters. More data and experience with the equipment are needed to address those risks. UV disinfection has been selected at sites to minimize undesirable byproducts in the effluent that may cause subsequent damage to aquatic life in receiving waters. Almost without exception, plant operations personnel preferred the UV systems over other methods of disinfection. The inherent relative safety of UV versus chlorine was frequently cited as the rationale for this preference, along with reduced labor requirements.

A survey identified 52 UV systems that currently operate in the U. S. and Canada. Inspections at six of these UV facilities provided insights on the practical application of UV disinfection theory that can be useful in future applications of this technology. The six sites provided examples of both successes and problems with the process. Most of the difficulties encountered were unrelated to the UV process itself, and instead resulted from electrical, mechanical, and hydraulic problems. In some cases the equipment design was inconsistent with good engineering application of the fundamentals of UV disinfection theory.

The primary recommendation derived from these on-site investigations is that the treatment plant design engineer must become as involved with the design of the UV process details as he is with the design of, for example, the activated sludge process. It also follows that those engineers need access to a body of data or some other guidance document that provides the information that will allow them to become actively involved. The recommendations in this article are offered as a first step toward disseminating information on UV systems.

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